LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR -89-2962

TITLE **EFFECTS OF MAIN-SEQUENCE MASS LOSS ON THE TURNOFF AGES OF GLOBULAR CLUSTERS**

LA-UR--89-2962

DE89 016784

AUTHOR(S) Joyce A. Guzik

SUBMITTED TO Institut d'Astrophysique de Paris
98 bis bd Arago
Paris, France 75014

EFFECTS OF MAIN-SEQUENCE MASS LOSS ON THE TURNOFF AGES OF GLOBULAR CLUSTERS

Joyce A. Guzik
Applied Theoretical Physics Division, Los Alamos National Laboratory

ABSTRACT

Willson, Bowen, and Struck-Marcell (1987) have proposed that globular cluster main-sequence turnoff ages can be reconciled with the lower ages of the Galaxy and universe deduced from other methods by incorporating an epoch of early main-sequence mass loss by stars of spectral types A through early-F. The proposed mass loss is pulsation-driven, and facilitated by rapid rotation. This paper presents stellar evolution calculations of Pop II ($Z=0.001$) mass-losing stars of initial mass 0.8 to 1.6 $M_\odot$, with exponentially decreasing mass loss rates of e-folding times 0.5 to 2.0 Gyr, evolving to a final mass of 0.7 $M_\odot$. The calculations indicate that a globular cluster with apparent turnoff age 18 Gyr could have an actual age as low as ~12 Gyr. Observational implications that may help to verify the hypothesis, e.g. low C/N abundance ratios among red giants following first dredge-up, blue stragglers, red giant deficiencies, and signatures in cluster mass/luminosity functions, are also discussed.

A continuing problem in stellar astrophysics is reconciling globular cluster ages with the age of the Galaxy and universe deduced by other methods. The Hubble age derived from galaxy redshifts (assuming zero cosmological constant) has been quoted by various groups at between 6.9 Gyr (de Vaucouleurs 1982) and 13 Gyr (Tammann and Sandage 1985). In contrast, globular cluster ages derived from standard stellar evolution theory are persistently older. Peterson (1987) uses the luminosity difference between the horizontal branch and main-sequence turnoff to determine ages of 41 globular clusters, and finds ages ranging from 11 Gyr (Pal 12) to 22 Gyr (NGC 6397). Janes and Demarque (1983) find from parametrized fits of 15 globular cluster sequences to those of theoretical isochrones that globular clusters have an age of about 16.6 ± 0.5 Gyr, and conclude that "globular cluster ages as young as 10 Gyr would would require large corrections [in the metallicity scale or mixing length] and would yield cluster properties inconsistent with observation."

L. A. Willson, G. H. Bowen and C. Struck-Marcell (1987) have recently proposed a modification to standard stellar evolution theory that could reduce the ages of globular clusters; they suggest that stars of spectral types between A and late-F or early G, arriving on the main sequence at its intersection with the Cepheid pulsation instability strip, may lose a substantial portion of their mass during the early part of their main sequence phase. The proposed mass loss is pulsation-driven, and facilitated by rapid rotation. Mass-loss rates as large as several times 10^{-9} $M_{\odot}$/yr, diminishing over timescales of 10^{8}-10^{9} years are expected. Mass loss ceases as envelope convection zones develop, channeling mechanical energy away from pulsation, and as magnetic fields develop, transferring angular momentum to the outflow and braking rotation. The final mass may depend upon metallicity, since the stellar mass corresponding to the red edge of the pulsation instability strip, or the mass at which stars develop convective envelopes, decreases with decreasing Z. In this scenario, the main-sequence turnoff becomes an invalid indicator of cluster age, as stars located at the apparent turnoff may have evolved from stars of higher initial mass; hence clusters may actually be younger than they appear. Willson et al. suggest that it is possible that globular clusters are no older than 7-10 Gyr.

This paper presents results of stellar evolution calculations for low metallicity stars including main-sequence mass loss, with the goal of determining the maximum globular cluster age reduction that can be achieved without generating inconsistencies with observed cluster properties. The evolution calculations were conducted using the Iben (1965) stellar evolution code as modified by Brunish (1982). The mass losing models have initial masses 0.8, 1.0, 1.2, 1.4 and 1.6 $M_{\odot}$, initial ^4He mass fraction $Y=0.25$, initial metal abundance $Z=0.001$, and constant mixing-length/pressure scale height ratio $\alpha_{Iben}=1.25$. The models lose mass with exponentially-decreasing mass loss rates of characteristic e-folding time τ, evolving toward a final mass of 0.7 $M_{\odot}$, so that the stellar mass as a function of time is

$$M(t) = 0.7 + (M_0 - 0.7)e^{-t/\tau} M_\odot$$

The effective temperature of the 0.7 $M_\odot$ model is ~5800 K, and the effective temperature of the 1.6 $M_\odot$ model is ~10,500 K, so we are postulating mass loss for stars between spectral types A0 and early-G. Mass-loss timescales of 0.5, 1.0 and 2.0 Gyr were considered.

Table 1 shows the main-sequence lifetimes, and Figures 1-4 show example evolutionary tracks of the models with 1 Gyr mass-loss timescales. A cluster with turnoff mass 0.7 $M_\odot$ and metallicity 0.001 would have an age deduced from standard evolution calculations of ~18 Gyr. If the mass-loss timescale is short compared to the main-sequence lifetime, the mass-losing models follow the normal constant-mass main sequence closely as they evolve down to 0.7 $M_\odot$; after this, their evolutionary tracks are nearly indistinguishable from the constant 0.7 $M_\odot$ model track for the remainder of main-sequence and first giant-branch evolution. However, their main-sequence lifetimes can be significantly shorter, as low as 8-12 Gyr, instead of 18 Gyr. Consulting Table 1, a cluster's age can be reduced from 18 Gyr to 12 Gyr if present turnoff stars were originally 1.4 $M_\odot$ with mass loss timescale 0.5 Gyr, 1.2 $M_\odot$ with mass-loss timescale 1.0 Gyr, or 1.0 $M_\odot$ with mass-loss timescale 2.0 Gyr. In this manner, clusters with well-delineated main-sequence turnoffs and giant branches can be generated that are in reality much younger than they appear from their main-sequence turnoff.

Table 1. Main-Sequence Lifetimes of Constant-Mass and Mass-Losing Models

	Mass-Loss Timescale (Gyr)			
Initial Mass ($M_\odot$)	...	0.5	1.0	2.0
0.70	17.9			
0.80	11.0		17.2	
1.00	5.1		15.1	12.4
1.20	2.6		12.3	7.6
1.40	1.4	13.1	9.1	
1.60	1.0	10.6		

Characteristics of some Population I clusters, e.g. broad main sequence turnoffs and blue stragglers, support the suggestion of such mass loss, but evidence may necessarily be more elusive in the case of globular clusters, as the epoch of early main sequence mass loss is completed for most, if not all cluster members. Compared to Population I clusters, globular clusters have well-delineated turnoffs and giant branches (Renzini and Pecci 1988), and more evidence that their blue straggler population can be accounted for by binary mass transfer

(Eggen and Iben 1989). However, the lack of evidence for a significant percentage of binaries among globular cluster stars (see e.g. Anthony-Twarog 1987, Richer and Fahlman 1984, 1986) and the presence of scores of blue stragglers in a number of globular clusters (Nemec and Harris 1987) weakens the binary–blue straggler connection, and main-sequence mass loss may offer an explanation for at least some of these blue stragglers as non-mass-losing stars that were left behind when other stars "slid down" to lower masses.

A significant portion of the first giant branch stars in many globular clusters, e.g. NGC 362, M5, M3, M15, M92, 47 Tuc, NGC 6752 (VandenBerg and Smith 1988), NGC 6171 (Smith 1988) and M55 (Richtler 1988), have low C/N abundance ratios inconsistent with standard stellar evolution. For M15 and M92, the onset of 1st dredge-up occurs at lower luminosity and is more pronounced than expected; for the other clusters, the CN abundances of giants at the same luminosity is bimodal; for 47 Tuc the bimodality persists down to the main sequence. Explanations proposed to date, deep mixing at some evolutionary phase (VandenBerg and Smith 1988), and binary mass-transfer or coalescence (Campbell 1986), have not been entirely satisfactory. Main-sequence mass loss also suggests an explanation for the above observations (see Table 2): Early evolution at higher mass would increase the proportion of the star exposed to partial CN-cycle processing; this material then lies closer to the surface, and can be mixed to the surface earlier by a convective envelope of usual depth. The bimodal abundances could be accounted for by giants with varying initial masses and mass-loss timescales. Finally, if a star loses over 1/2 of its mass on the main-sequence, the CN-processed material is already exposed during the main-sequence phase.

Table 2. $X(^{12}C)/X(^{14}N)$ of mass-losing models with final mass 0.7 $M_\odot$ after 1st dredge-up phase

	Mass-Loss Timescale (Gyr)		
Initial Mass ($M_\odot$)	0.5	1.0	2.0
0.80		3.04	
1.00		2.97	2.92
1.20		1.76	1.33
1.40	0.679	0.471	
1.60	0.139		

Clusters with members that experienced main sequence mass loss should show a deficiency of giants, since stars currently populating the giant branch had higher progenitor masses, and should exhibit signatures of such mass loss in their mass/luminosity functions. The deficiency may not appear as marked as expected, as the initial mass functions deduced from main-sequence luminosity functions would be flatter if the effects of main sequence mass loss were taken into account. Table 3 shows the percentage expected giant deficiency assuming a Salpeter (1955) IMF $\phi(m) = m^{-(1+x)}$ with two different slopes x, and for different mass-loss e-folding times, assuming that an age reduction from 18 Gyr down to 12 Gyr is desired.

Table 3. Expected % giant deficiency for globular cluster age reduction from 18 Gyr to 12 Gyr

	Mass-Loss e-folding Time (Gyr)		
IMF x	0.5	1.0	2.0
-1.35	82	72	57
0.0	52	42	29

Some evidence exists for giant deficiencies among Pop. II clusters. Green (1981) found a few globular clusters toward the Galactic center (M55, M10 and NGC 6171) that appear to have a real deficiency of bright giants. A number of sparse globular clusters (e.g. E3, Hesser et al. 1984; Pal 12, Harris and Canterna 1980; and AM-4, Inman and Carney 1987) also have few (or no) giants relative to their more-populous counterparts. Sil'chenko (1987) uses integrated B-V color, which samples primarily the giant and subgiant branch as opposed to the main-sequence stars, to derive the ages of 10 globular clusters; he finds that these populations indicate ages of only 6-12 Gyr for most of the clusters, and an age of 14 Gyr for the oldest cluster, NGC 6397 (dated by Peterson at 22 Gyr). The IMF derived for 47 Tuc (Meylan 1989) changes slope sharply at the main-sequence turnoff, from nearly flat, x = 0.2-0.3 for main-sequence stars, to x = 2.75-3.5 for giant-branch stars, highlighting a potential giant deficiency and excess of main-sequence turnoff stars. Many low-Z globular clusters (M5, M15, M68, M92, NGC 6397 and NGC 6752; see e.g. McClure et al. 1986) exhibit a flattening in their main-sequence luminosity functions at $6<M_V<7$, a little below the main-sequence turnoff; this could be indicative of an expected pileup of stars where mass-loss becomes ineffective. While these findings are suggestive, they are not necessarily universal, and it may prove very difficult to explain why main-sequence mass loss should occur in some, but not all, clusters. Of course, if some old clusters are exempt, the advantage of reconciling globular cluster ages with the Hubble age is lost.

References

Anthony-Twarog, B.J. 1987, Astron. J. 93, 1454

Brunish, W.M. and Truran, J.W. 1982, Ap. J. 256, 247

Campbell, B. 1986, Ap. J. 307, 750

Demarque, P. 1980, in IAU Symposium 85: Star Clusters, ed. J. Hesser, p. 281

de Vaucouleurs, G. 1982, Nature 299, 303.
Eggen, O.J. and Iben, I. 1989, Astron. J. 97, 431
Green, E.M. 1981, in Astrophysical Parameters of Globular Clusters, eds. A.G. Davis Philip and D.S. Hayes, p. 427.
Harris, W.E. and Catema, R. 1980, Ap. J. 239, 815.
Hesser, J.E., McClure, R.D., Hawarden, T.G., Cannon, R.D., Von Rudloff, R., Kruger, B and Egles, D. 1984, P.A.S.P. 96, 406.
Iben, I. 1985, Ap. J. 141, 993.
Inman, R.T and Carney, B.W. 1987, Astron. J. 93, 1166.
Janes, K. and Demarque, P. 1983, Ap. J. 264, 206.
McClure, R.D., VandenBerg, D.A., Smith, G.H., Fahlman, G.G., Richer, H.B., Hesser, J.E., Harris, W.E., Stetson, P.B. and Bell, R.A. 1986, Ap. J. 307, L49.
Meylan, G. 1989, Astron. Ap. 214, 106.
Nemec, J.M. and Harris, H.C. 1987, Ap. J. 316, 172.
Peterson, C.J. 1987, P.A.S.P. 99, 1153.
Renzini, A. and Fecc . F.F. 1988, Ann. Rev. Astron. Ap. 26, 199.
Richer, H.B. and Fahlman, G.G. 1984, Ap. J. 277, 227.
Richer, H.B. and Fahlman, G.G. 1986, Ap. J. 304, 273.
Richtler, T. 1988, Astron. Ap. 204, 101.
Sil'chenko, O.K. 1987, Soviet Astron. 31, 359 (Astron. Zhurnal 64, 686).
Smith, G.H. 1988, Astron. J. 95, 755.
Tammann, G.A. and Sandage, A. 1985, Ap. J. 294, 106.
VandenBerg, D.A. and Smith, G.H. 1988, P.A.S.P. 100, 314
Willson, L.A., Bowen, G.H. and Struck-Marcell, C. 1987, Comm. Ap. 12, 17

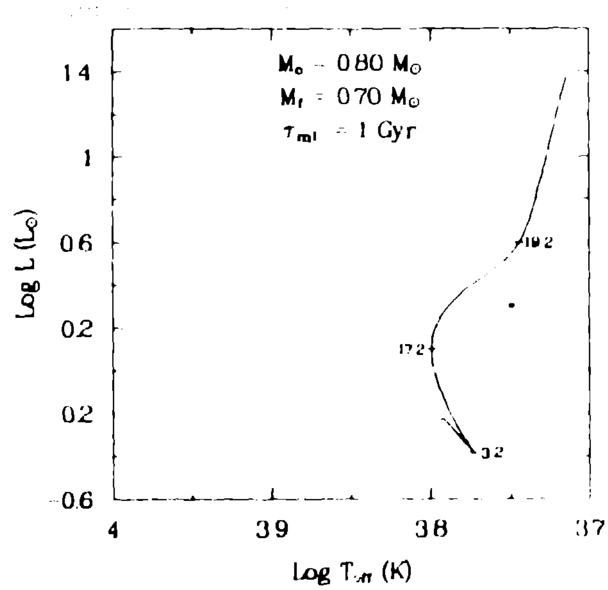

Fig. 1. Evolutionary track of mass-losing model with Z=0.001, initial mass 0.8 $M_\odot$, final mass 0.7 $M_\odot$, and e-folding mass-loss timescale 1 Gyr.

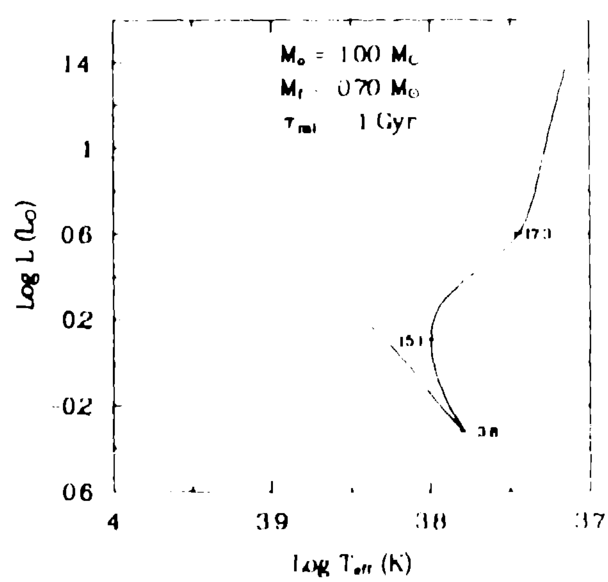

Fig. 2. Evolutionary track of mass-losing model with Z=0.001, initial mass 1.0 $M_\odot$, final mass 0.7 $M_\odot$, and e-folding mass-loss timescale 1 Gyr.

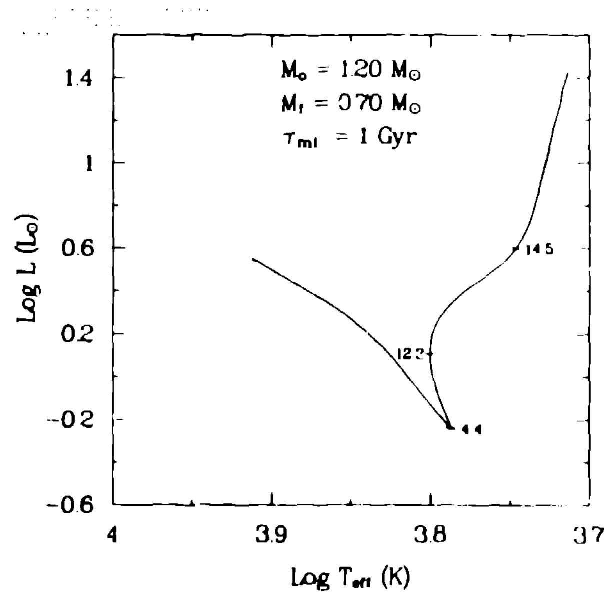

Fig. 3. Evolutionary track of mass-losing model with Z=0.001, initial mass 1.2 $M_\odot$, final mass 0.7 $M_\odot$, and e-folding mass-loss timescale 1 Gyr.

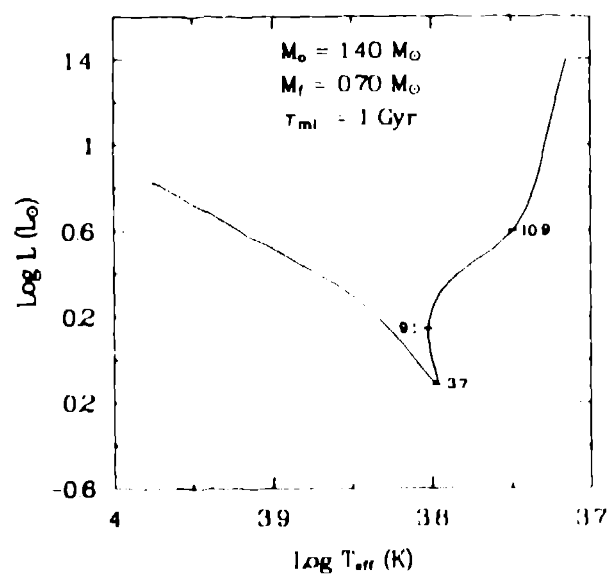

Fig. 4. Evolutionary track of mass losing model with Z 0.001, initial mass 1.4 $M_\odot$, final mass 0.7 $M_\odot$, and e folding mass-loss timescale 1 Gyr